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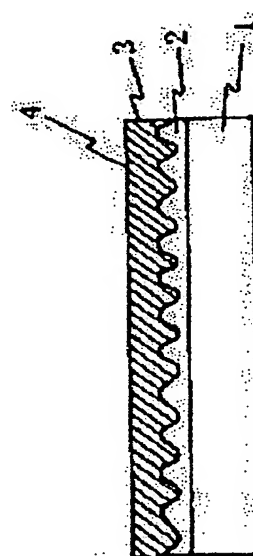
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(54) TRANSMISSION TYPE SURFACE RELIEF DIFFRACTION GRATING

(57)Abstract:

PURPOSE: To enhance diffraction efficiency by forming a relief layer of no refractive index and a coat layer of (n) refractive index flat on the surface with respect the wavelength of light incident on the diffraction grating, and specifying the refractive indices no and (n).

CONSTITUTION: The relief layer 2 made of transparant resin changed in thickness like a sine wave is formed on a transparent flat glass 1, and a coat layer 3 made of transparent resin of (n) refractive index is formed on the layer 2, with the surface 4 of the layer 3 flattened. The diffractive grating thus obtained is raised in diffraction efficiency, with its depth kept constant, by setting the difference of refractive index between the layers 2, 3. The diffraction efficiency can be raised by forming the layer 2 of no refractive index and the layer 3 of (n) so as to satisfy $n > 2n_0 - 1$.



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⑭ 透過型表面レリーフ回折格子

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明 細 書

1 発明の名称

透過型表面レリーフ回折格子

2 特許請求の範囲

回折格子に入射する光の波長に対する屈折率 n_0 のレリーフ層、その上に表面が平坦な屈折率 n の被覆層を有し、これら両層の屈折率 n_0 、 n が

$$n > 2 n_0 - 1$$

の関係にあることを特徴とする透過型表面レリーフ回折格子

3 発明の詳細な説明

この発明はレリーフ表面に高屈折率層を配することにより、回折効率を向上させたレリーフ回折格子に関する。

均一な屈折率を有する透明媒質が場所により厚さを変え、その表面にレリーフ状の凹凸が作られている回折格子は、表面レリーフ回折格子と呼ばれる。特にホトレジストに干渉縞を記録して作られる回折格子は、正弦波状の凹凸を有

し、入射光に対する回折効率も高く、光走査用ホログラム、光導波路でのグレーティングカプラ、光通信等、オプトエレクトロニクスでの用途が拡がりつつある。

第1図は透明平板ガラス1上に厚みが正弦波状に変化した透光性樹脂層2が形成されたレリーフ回折格子を示す。このような透過型レリーフ回折格子はホログラフィック技術により製作されるが、そのための光学系を第2図に示す。レーザ光源5からの光をレンズ6で平行光とし、対物レンズ7でピンホール8に集束する。ピンホール8を通過した発散光はレンズ9により再び平行光となる。この平行光はピンホール8のフィルタリング効果によりほぼガウス分布状の強度分布を有する。分布補正蒸着フィルタ10は逆ガウス分布の透過率を持ち、ガウス強度分布を有する平行光が透過すると一様分布の平行光となる。この一様分布の平行光はビームスプリッタ11で2つの光束に分割され、1つは反射鏡12で他方は反射鏡13で反射され、共に

ガラス基板1上に塗布されたホトレジスト2上に重なり合うように照射される。このようにすれば、ホトレジスト2上では2つの光束は干渉し、明暗の縞を形成し、ホトレジスト2はこの明暗の縞に応じて感光する。ホトレジストとしてポジタイプのもを用いた場合は、光照射後、現像処理を行なえば感光した部分が除去され、第1図のような正弦波状のレリーフが形成される。

このようにして作られる回折格子は、ホトレジストの材料的な特性により、格子間隔Dが小さくなるにつれて格子の深さhを深くすることが困難となる。

発明者は先に透過型異面レリーフ回折格子で高い回折効率を得るためには、格子の深さhが回折格子に入射する光の波長 λ に対して

$$h/\lambda > 0.4$$

の条件を満たすことが必要であることを見出した。

しかし、現在もつとも解像度の高いポジ型ホトレジストを用いた場合でも、ホログラムの記

(3)

が一定で回折効率を高くするにはレリーフ界面での屈折率差 Δn を大きくすればよい。

第1図のような従来の格子構造では、レリーフ面における屈折率差 Δn_1 はレリーフ層2の屈折率 n_0 に対して $n_0 - 1$ となる。一方、第3図に示すこの発明の実施例においては、屈折率差 Δn_2 は $n - n_0$ となる。従つて被覆層3を設けたことによつて回折効率が高まるためには

$$\Delta n_2 > \Delta n_1$$

すなわち

$$n - n_0 > n_0 - 1$$

$$\therefore n > 2n_0 - 1$$

を満足するように被覆層の屈折率 n を選べばよい。

レリーフ層2としてポジ型ホトレジスト層を用いた場合 $n_0 = 1.65$ である。従つて被覆層3の屈折率 n は2.3以上であることが必要となる。

このような高屈折率の物質は高分子材料中には見当たらない。無機材料の1例として製作の容

(5)

録光の波長 $\lambda = 0.4416 \mu\text{m}$ の場合、格子間隔Dが約 $0.3 \mu\text{m}$ 以上でしか上記の条件を満たすことが出来ない。このため、格子間隔Dが $0.3 \mu\text{m}$ 以下の場合には高い回折効率を得ることができない。

この発明は、上記のように格子の深さhが小さい異面レリーフを有する透過型異面レリーフ回折格子にあつても高い回折効率を得ようとするものである。

すなわち、第1図に示すような透過型異面レリーフ回折格子においては、格子の深さhが深くなると回折効率が上がるが、一方、深さhが一定の場合、回折格子を形成する媒質の屈折率 n_0 が大きくなれば回折効率が上がる。

この効果を利用し、第3図に示す実施例では透明平板ガラス1上に正弦波状に厚みの変化した透光性樹脂のレリーフ層2が形成され、その上に屈折率 n の透明材料からなる被覆層3が設けられ、その表面4は平坦となつている。このような構造の回折格子において、格子の深さh

(4)

易なものとして n が2.6程度である As_2S_3 をあげることが出来る。 As_2S_3 はアモルファス半導体であり蒸着によつて容易に回折格子表面に被覆層を形成することが出来る。

被覆層の効果は格子深さhの大きいものでも同じであるが、上述のように格子間隔Dが $0.3 \mu\text{m}$ 以下のものでは深さhを大きくできないので、この発明による回折効率の向上が特に必要な対象である。そしてこの場合には被覆層3の厚みを数 μm 以上とすれば、レリーフ層2の凹凸形状は埋められ、第3図の面4のように平坦な面となる。

1例をあげれば、格子間隔 $D = 0.447 \mu\text{m}$ 、格子の深さ $h = 0.25 \mu\text{m}$ の場合、 As_2S_3 を $2 \mu\text{m}$ 程度蒸着することにより平坦面4が得られ、蒸着前の回折効率2.5%が被覆層により回折効率4.5%へと向上した。

以上、この発明をホログラフィック技術によつて製作した正弦波状の透過型異面レリーフ回折格子に実施した場合を例として説明したが、

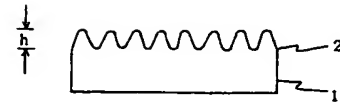
(6)

レリーフ形状は三角形状、矩形状等任意のものでよく、ホログラフィック技術によらず、けがきによつて製作した回折格子についても同様に有効である。

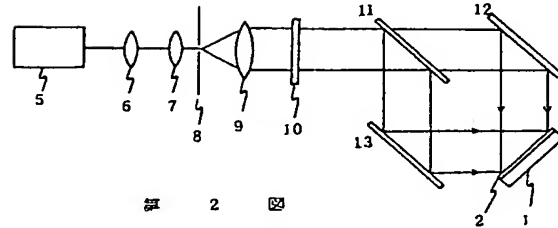
4. 図面の簡単な説明

第1図は通常の正弦波状レリーフ回折格子の構造を示す断面図、第2図はホログラフィック光学系光路図、第3図はこの発明の1実施例の構造を示す断面図

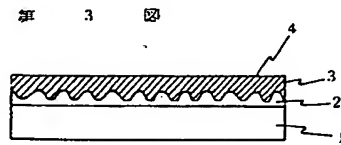
1：ガラス基板 2：ホトレジストレリーフ層 3：被覆層 4：被覆層表面



第 1 図



第 2 図



第 3 図

特許出願人 株式会社 リコー
出願人代理人 弁護士 佐 藤 文 男
(ほか1名)

(7)

Rectangular surface-relief transmission gratings with a very large first-order diffraction efficiency ($\sim 95\%$) for unpolarized light

Hendrik J. Gerritsen and Mary Lou Jepsen

Computer optimization shows that the first-order diffraction efficiency of a lossless-transmission surface-relief grating with a rectangular surface profile can be made very large ($\sim 95\%$) simultaneously for light of TE and TM polarizations incident near the Bragg angle by the proper choice of the fill factor. The case for visible light incident close to the Bragg angle on unslanted gratings with periodicities corresponding to Bragg angles of 30° , 37.5° , and 45° is presented. The refractive index of the grating material was chosen in the range between 1.2 and 2. © 1998 Optical Society of America

OCIS codes: 050.1960, 050.1950, 050.7330, 090.1760.

1. Introduction

It has been well established in theory (see, for example, Ref. 1) and verified by experiment²⁻⁴ that rectangular surface gratings can have a very large first-order diffraction efficiency ($\sim 95\%$) when the incident angle of the light is at or near the Bragg angle and all orders of diffraction are evanescent except the zeroth order and one first order. Very little attention has been given to date to the effect of polarization, and most research—including that reported in Refs. 1–3—has involved TE incident light in which the electrical vector is transverse to the plane of incidence and thus parallel to the grooves of the diffraction grating.

In many important practical applications of such gratings such as spectroscopy, optical diffractive devices, and in diffractive "daylighting" (i.e., bringing daylight deep into a room), it is important that as large an efficiency as possible occurs at a given depth for unpolarized light, that is, for both TE and TM polarizations simultaneously. In diffractive daylighting a diffraction grating is placed in contact with a window; it diffracts a large fraction of the incident

light upward toward the ceiling to project light in the back of a room.⁵

We discovered in the course of computer simulations by using a rigorous coupled-wave theory program, developed by Jepsen and based on Ref. 1, that this goal of high diffraction efficiency for both TE and TM is possible and can be attained over a large range of important parameters, namely, the refractive index and the grating spacing Λ [with the corresponding Bragg angle θ_B , where $\theta_B = \arcsin(\lambda/2\Lambda)$] by the proper choice of the fill factor f . The fill factor f is 0.5 for a grating in which the dielectric ridges have the same width as the air-filled valleys; this case is also referred to as a square grating. In general the fill factor is defined as the ratio of the width of the dielectric ridge over the grating periodicity Λ (which is, of course, the sum of the width of the dielectric ridge and the air valley).

One rather recent study⁶ did consider polarization effects on efficiency and demonstrated that, by a proper choice of parameters (in that study the parameter was the depth, not the fill factor, which was taken as 0.50), gratings with high diffraction efficiency for TE incident light and near zero for TM incident light could be obtained. This is the opposite of what is of interest here.

2. Computational Results

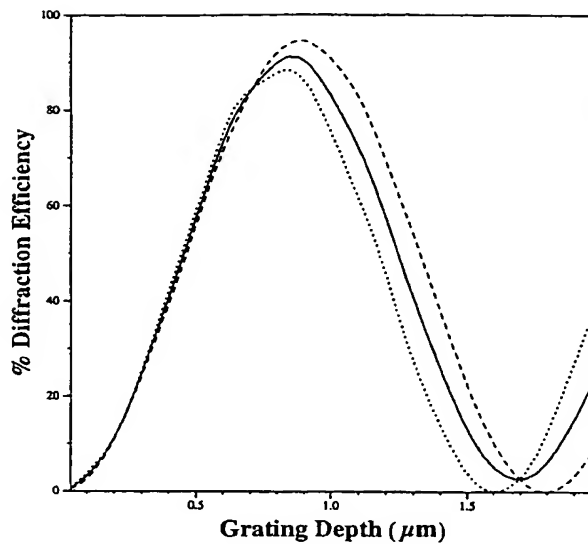
We first consider the case of $\lambda = \Lambda = 0.55 \mu\text{m}$ and 30° incidence, so (only) the first-order diffracted beam exits at -30° because of its similarity to the case considered in Ref. 1 and also because it is in the range of useful parameters for a daylighting structure.⁵

When this study was performed, the authors were with the Department of Physics, Brown University, Providence, Rhode Island 02912. M. L. Jepsen is now with Philips Research, 345 Scarborough Road, Briarcliff Manor, New York 10520.

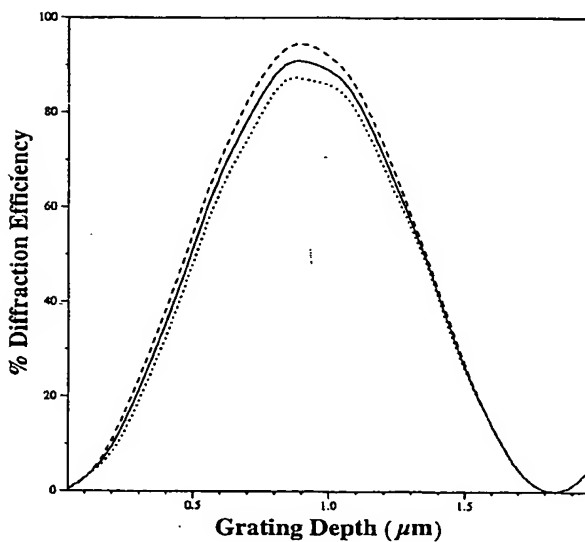
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(a)

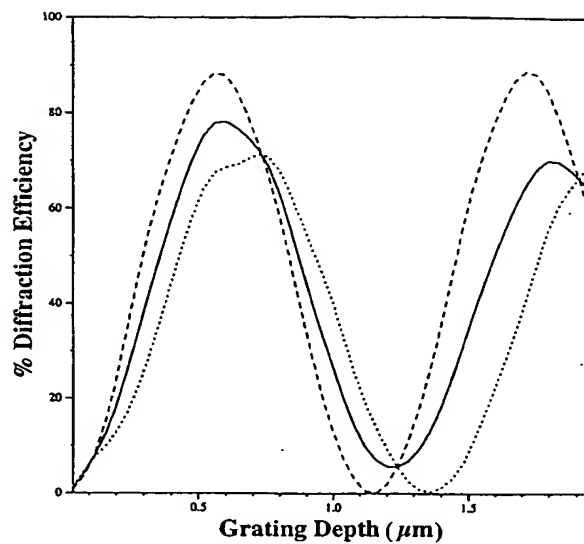


(b)

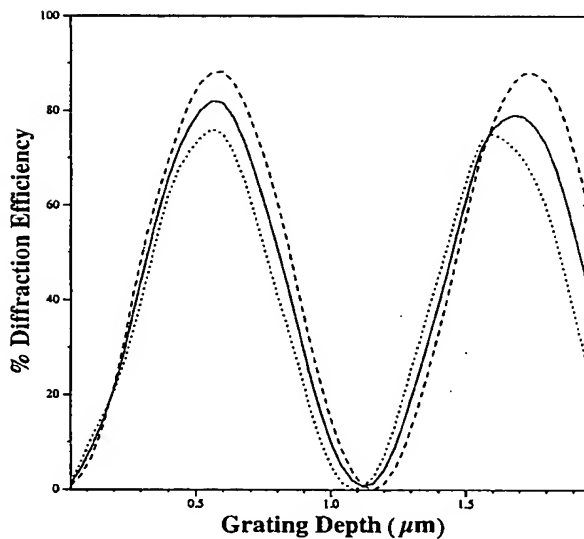
Fig. 1. Diffraction efficiency for first-order diffracted light with the following parameters: $\lambda = \Lambda = 0.55 \mu\text{m}$, $\theta_B = 30^\circ$, and $n = 1.58$. Curves: the (TE + 1) order transmitted; ----- the (TM + 1) order transmitted; — the average or unpolarized diffracted light. (a) Fill factor of $f = 0.50$. (b) Fill factor of $f = 0.56$.

We ignored reflections at the flat exit interface. Such reflections can easily be calculated by use of the Fresnel equations or, in practice, almost eliminated through application of an antireflex coating. For the calculations, we used the rigorous coupled-wave theory.¹

Figure 1(a) shows the depth dependence of the diffractive efficiency for $f = 0.50$ and for $n = (2.50)^{1/2} = 1.58$, as was used in Ref. 1. The TE and the TM curves are not far apart, and a maximum



(a)



(b)

Fig. 2. Diffraction efficiency for first-order diffracted light with the same parameters as for Fig. 1 except that $n = 1.85$. Curves: the (TE + 1) order transmitted; ----- the (TM + 1) order transmitted; — the average or unpolarized diffracted light. (a) Fill factor of $f = 0.50$. (b) Fill factor of $f = 0.42$.

diffraction efficiency of 91% for unpolarized light and a depth of $0.88 \mu\text{m}$ results. The maximum efficiency for TE polarization is 88% at a depth of $0.84 \mu\text{m}$, close to the value of 89% at a depth of 1.55λ , corresponding to $0.85 \mu\text{m}$, given in Ref. 1. Figure 1(b) shows that, with a fill factor of $f = 0.56$, the TE and the TM maxima coincide, leading to an optimum efficiency for unpolarized light of 91% at a depth of $0.90 \mu\text{m}$. Calculations show that increasing the values of the fill factor to greater than 0.56 results in a shift of both the TE and the TM curves

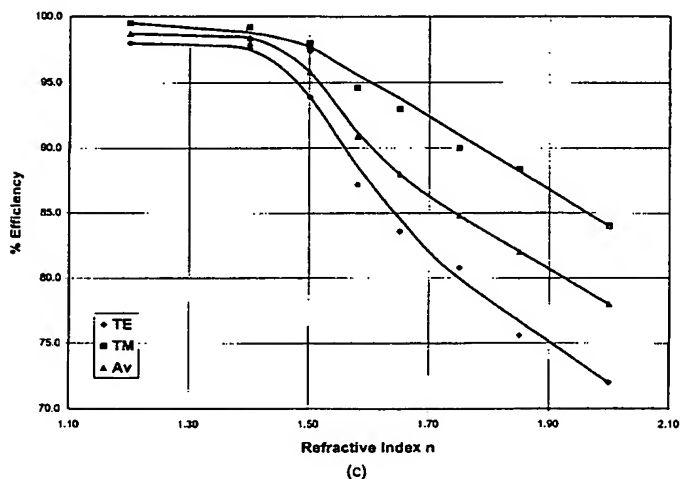
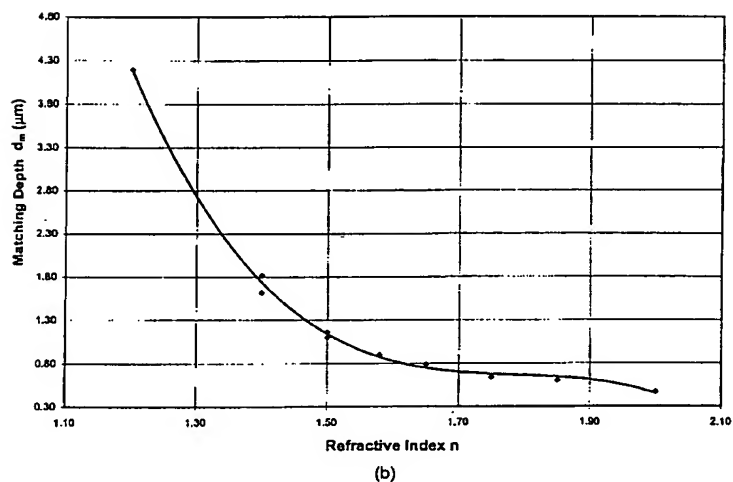
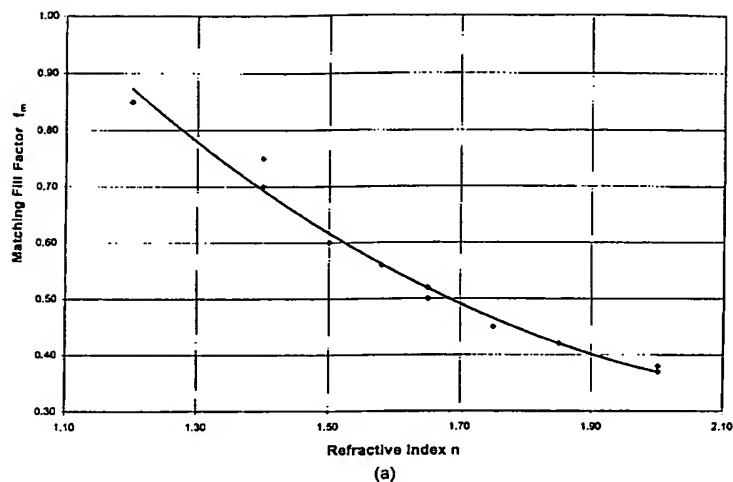
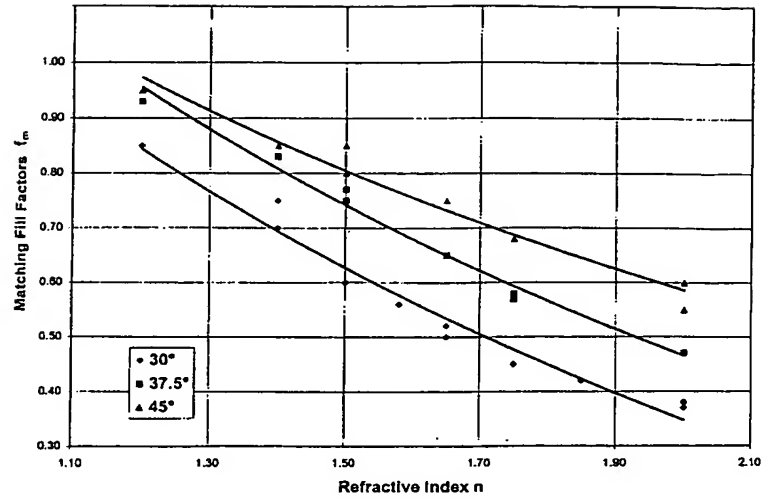


Fig. 3. For $\lambda = \Lambda = 0.55 \mu\text{m}$ and $\theta_B = 30^\circ$: (a) Matching fill factor f_m , for which the maxima of the diffraction efficiencies for TE and TM light occur at the same depth d_m , as a function of the refractive index. (b) Depth d_m as a function of the refractive index. (c) First-order diffraction efficiencies as a function of the refractive index n .

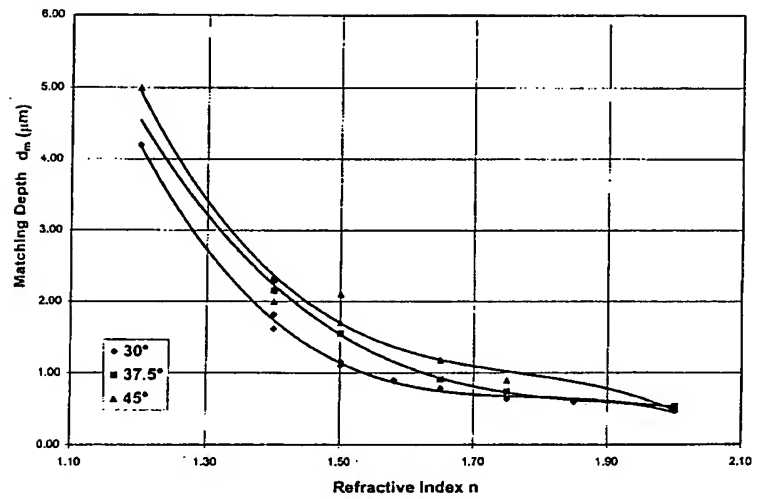
to larger depth values. However, the TE curve [which was to the left of the TM curve in Fig. 1(a) for a value of $f = 0.50$] shifts more rapidly, so for f values greater than 0.56 it moves to the right of the

TM curve, resulting in a drop of the unpolarized efficiency.

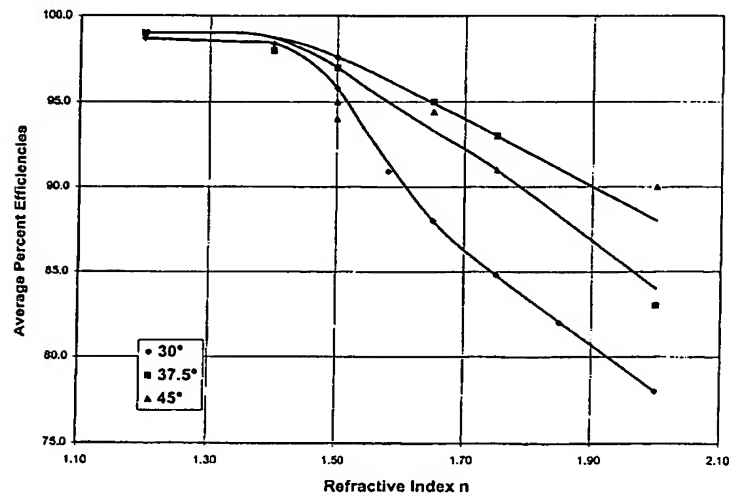
We show in Fig. 2(a) the same depth dependence as in Fig. 1(a) except that the refractive index is 1.85



(a)

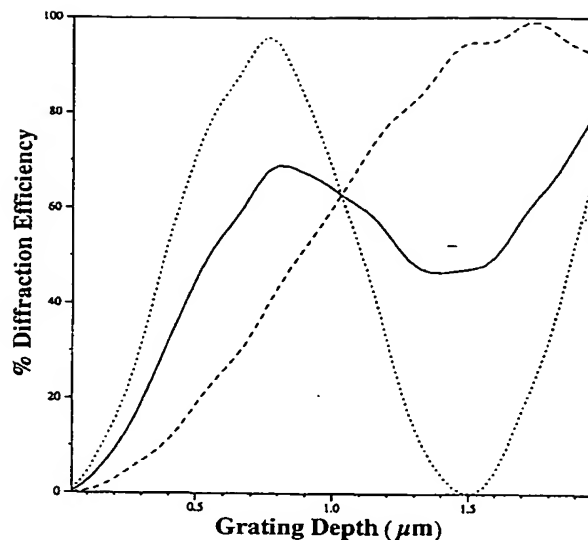


(b)

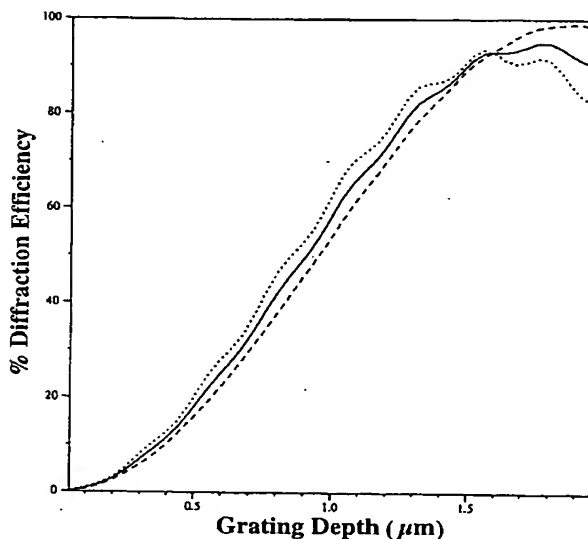


(c)

Fig. 4. For three grating spacings ($\lambda = 0.55 \mu m$) of $\Lambda = 0.55 \mu m$ ($\theta_B = 30^\circ$), $\Lambda = 0.4517 \mu m$ ($\theta_B = 37.5^\circ$), and $\Lambda = 0.3889 \mu m$ ($\theta_B = 45^\circ$): (a) Matching fill factor f_m for which the maxima of the diffraction efficiency for TE and TM light occur at the same depth as a function of the refractive index. (b) Depth d_m as a function of refractive index. (c) First-order diffraction efficiencies as a function of the refractive index n for unpolarized light.



(a)



(b)

Fig. 5. (a) First-order diffraction efficiencies for a grating with $\lambda = 0.55 \mu\text{m}$, $\Lambda = 0.3889 \mu\text{m}$, $\theta_B = 45^\circ$, $n = 1.50$, and $f = 0.50$. (b) First-order diffraction efficiencies for a grating with $\lambda = 0.55 \mu\text{m}$, $\Lambda = 0.3889 \mu\text{m}$, $\theta_B = 45^\circ$, $n = 1.50$, and $f = 0.80$.

rather than 1.58. Now, to obtain the optimal diffraction efficiency for unpolarized light, one must reduce f to $f = 0.42$, where the two curves peak simultaneously at a depth of $0.55 \mu\text{m}$ and the unpolarized diffraction efficiency (the average of the TE and TM efficiency) is 81%, as shown in Fig. 2(b). We designate this optimal fill factor by f_m and the corresponding optimal depth by d_m .

We show in Fig. 3(a) how the optimal fill factor f_m varies with the refractive index n for a range of typical refractive indices of transparent solids. Figure 3(b) shows, for the same range of refractive-index

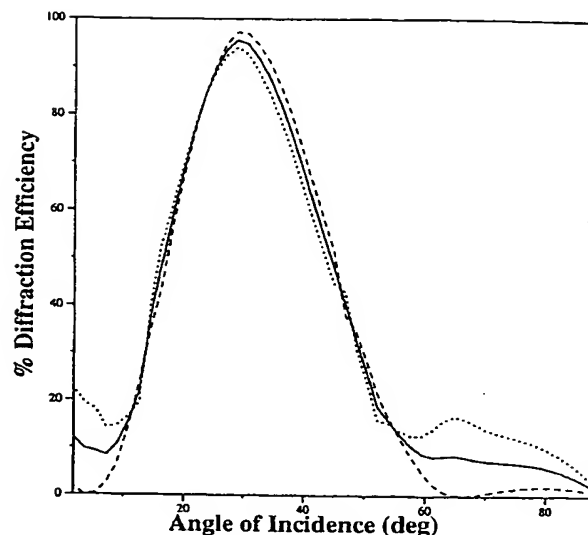


Fig. 6. Angular dependence of the efficiency of the first-order diffracted light of a wavelength of $\lambda = 0.55 \mu\text{m}$ for a grating with a periodicity of $\Lambda = 0.55 \mu\text{m}$, a refractive index of $n = 1.50$, a fill factor of $f = 0.60$, and a depth of $d_m = 1.16 \mu\text{m}$. Curves: Dotted curve, the (TE + 1) order; dashed curve, the (TM + 1) order; and solid curve, the average diffracted efficiency.

values, the grating depths d_m for optimal efficiency that correspond to the optimal fill factor f_m , and Fig. 3(c) shows the corresponding diffractive efficiency for the TE and the TM polarizations (right-hand side). One can see that, for a square grating with a refractive index of 1.65, as is typical for photoresist, a 90% efficiency is calculated for unpolarized light, which close to earlier reported measurements.⁴

For a refractive index of 1.4 near that of fused silica, an efficiency of 98% for unpolarized light is calculated for a fill factor of 0.65. A square grating of this material would have a 93% efficiency for unpolarized light, which is close to a recently reported value of 90% (Ref. 7) for such a grating.

The refractive-index range and individual values chosen reflect values typical for glass and plastics.⁸ For glass the practical range starts at $n = 1.46$ with fused quartz. (The refractive-index values quoted are for the yellow sodium D line). Lower values, such as 1.40 for fluorite glass and values from 1.4 to 1.0 for silica aerogels, can be obtained. The upper values of the range are $n = 1.98$ for phosphate flint and $n = 1.96$ for dense lanthanum flint. The value of $n = 1.58$ used in this paper corresponds to common light barium flint glass, and the value of $n = 1.85$ corresponds to medium-dense lanthanum flint glass.

The range for optical plastics is more restricted and typically runs from $n = 1.49$ for poly(methyl methacrylate) (plexiglass) and glass resin up to $n = 1.68$ for poly(vinyl naphthalene). The value of $n = 1.58$ corresponds to polycarbonate, whereas another common plastic, polystyrene, has a refractive index of $n = 1.59$.

We now consider how these results change for gratings with a periodicity different from $0.55 \mu\text{m}$ and

thus a different Bragg angle of incidence. This is a multidimensional problem because the efficiency of the grating for TE or TM polarized light at a given wavelength, here mostly taken as $0.55\text{ }\mu\text{m}$, depends on the following variables: grating depth, refractive index, periodicity, angle of incidence, and fill factor.

Because we are concerned here with high efficiency and thus Bragg diffraction on an unslanted grating, we have between the angle of incidence and the periodicity the relation $2 \sin \theta \Lambda = \lambda$, so we can replace the two variables periodicity Λ and angle of incidence θ with one. Similarly we can find for a certain periodicity and refractive index those values for the grating depth and the fill factor that simultaneously optimize the efficiency for TE and TM polarized light. Having done this leaves us with a more manageable set of variables, so we can now plot the unpolarized efficiency as a function of the Bragg angle for various refractive indices, with the depth and the fill factor taking values that optimize them. This procedure was done on a computer for additional Bragg angles of 37.5° and 45° , and the results are shown in Figs. 4(a)–4(c), which show two new angles plotted together with the data for 30° . Some interesting conclusions can be drawn from Fig. 4 when the data are applied to the case of daylighting, in which typically a combination of gratings varying in Bragg angle between 30° and 45° is used so that spectral mixing is obtained, i.e., whitish light is diffracted onto the ceiling.⁵ On the basis of Figs. 4(a) and 4(c), one would choose a grating material with a refractive index between 1.5 and 1.6. The efficiencies in that case are in the 90% to 95% range, and the fill factors must be in the range of 0.55 to 0.82. For smaller refractive-index values the efficiency still increases a little, but the fill factor for the finest grating begins to approach unity, leading to difficulties in producing and maintaining such gratings. For larger refractive-index values, on the other hand, the main disadvantage is that the efficiencies drop down into the 80% to 90% range. Also worth mentioning is that, for the coarsest grating considered with a periodicity of $0.5\text{ }\mu\text{m}$, very high diffraction efficiencies for unpolarized light are obtained with square gratings in the range of refractive indices for common optical materials, i.e., from 1.5 to 1.7. Figures 5(a) and 5(b) show that a square grating is not a good choice for a grating having a periodicity of $0.3889\text{ }\mu\text{m}$ ($\theta_B = 45^\circ$) and a refractive index of 1.5, which is illuminated with unpolarized light.

Because one important application of these gratings is for diffractive daylighting, it is thus of significance to know the efficiency not only for a wavelength of $0.55\text{ }\mu\text{m}$, the middle of the visible spectrum, but also for the red and the violet wavelength. Also, it is important, in particular, to know the variation of the efficiency with a changing angle of incidence. In this respect the broad and not the sharply peaked response of such relief gratings compares favorably with the narrow-band response typical of volume gratings.

Figures 6, 7, and 8 are chosen as typical examples

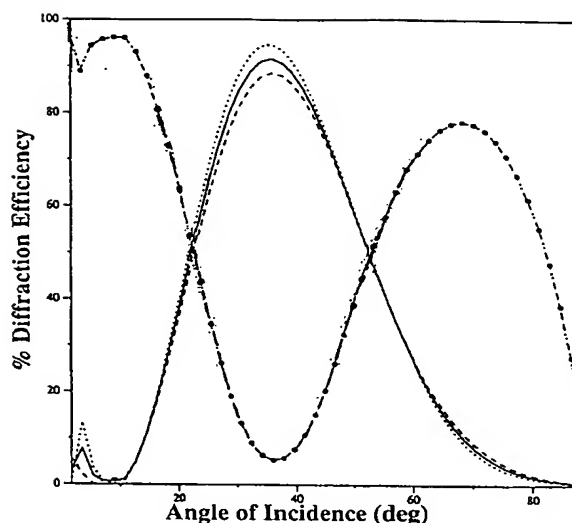


Fig. 7. Angular dependence of the efficiency of the first-order diffracted light of a wavelength of $\lambda = 0.65\text{ }\mu\text{m}$ on a grating with periodicity $\Lambda = 0.55\text{ }\mu\text{m}$, refractive index $n = 1.50$, a fill factor of $f = 0.60$, and a depth of $d_m = 1.16\text{ }\mu\text{m}$. Curves: Dotted curve, the (TE + 1) order; dashed curve, the (TM + 1) order; solid curve, the average diffracted efficiency; and curve with black circles, the average transmitted efficiency.

in which, for a grating with a refractive index of $n = 1.50$, a fill factor of $f = 0.60$, a period of $\Lambda = 0.55\text{ }\mu\text{m}$, and a depth of $d_m = 1.16\text{ }\mu\text{m}$, the unpolarized efficiency is plotted against the incident angle for green, red, and violet light. One can note that high effi-

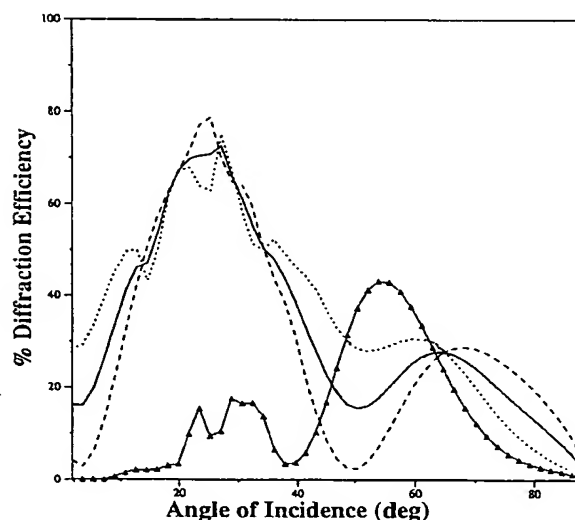


Fig. 8. Angular dependence of the efficiency of the first-order diffracted light of a wavelength of $\lambda = 0.45\text{ }\mu\text{m}$ on a grating with a periodicity of $\Lambda = 0.55\text{ }\mu\text{m}$, a refractive index of $n = 1.50$, a fill factor of $f = 0.60$, and a depth of $d_m = 1.16\text{ }\mu\text{m}$. Curves: Dotted curve, the (TE + 1) order; dashed curve, the (TM + 1) order; solid curve, the average first-order diffracted efficiency; and curve with black triangles, the second-order diffraction efficiency.

ciencies for unpolarized light occur over a broad range of incident angles. For red light with $\lambda = 0.65 \mu\text{m}$, most of the light that is not diffracted goes straight through in the zeroth order. For violet light this is not quite so, and near the peak diffraction at 25° with a 78% efficiency for the first order, the zeroth order receives approximately 7% of the light. Calculations show that now a +2 order propagates and carries approximately 14% of the light energy. The corresponding curve is shown in the Fig. 8. For daylighting applications this means that 90% of the violet light will be diffracted upward to the ceiling at a Bragg angle of 25° . It also shows that, for wavelengths shorter than the one for which at the Bragg angle all other diffracted orders except the +1 order are just not propagating, attention must be paid to other diffraction orders that can now propagate.

3. Conclusion

We have shown that it is possible to optimize the diffraction efficiency for TE and TM polarized light of a wavelength of $0.55 \mu\text{m}$ incident on an unslanted transmission grating with a rectangular profile and periods between 0.55 and $0.3889 \mu\text{m}$, so they peak at the same value of grating depth d_m . To do this, one must choose the correct fill factor f , depending on the refractive index n of the grating dielectric and the period Λ .

It has been shown that the best refractive-index value is in the range between 1.5 and 1.6, which is typical for glasses and common plastics. The corresponding fill factors are then in the range between 0.55 and 0.82. The efficiency for unpolarized light is then in the 90% to 95% range.

It will be an interesting challenge to construct grat-

ings with the proper f_m value. Extensions of photolithography and ion-beam-etching techniques or diamond-etching grating-ruling techniques suggest themselves.

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